Published in final edited form as:

J Speech Lang Hear Res. 2012 October ; 55(5): 1373–1386. doi:10.1044/1092-4388(2012/11-0358).

The Effect of Technology and Testing Environment on Speech Perception using Telehealth with Cochlear Implant Recipients

Jenny L. Goehring, Michelle L. Hughes, Jacquelyn L. Baudhuin, Daniel L. Valente, Ryan W. McCreery, Gina R. Diaz, Todd Sanford, and Roger Harpster

Abstract

Purpose—The current study evaluated the effect of remote system and acoustic environment on speech perception via telehealth with cochlear implant recipients.

Method—Speech perception was measured in quiet and in noise. Systems evaluated were: Polycom visual concert (PVC) and a hybrid presentation system (HPS). Each system was evaluated in a sound-treated booth and a quiet office.

Results—For speech in quiet, there was a significant effect of environment with better performance in the booth compared to the office; there was no effect of system (PVC or HPS). Speech in noise revealed a significant interaction between environment and system. Subjects' performance was poorer for PVC in the office while performance in the sound booth was not significantly different for the two systems. Results from the current study were compared to results for the same group of subjects from an earlier study; results suggested poorer performance at remote sites in the previous study was primarily due to environment, not system.

Conclusions—Speech perception was best when evaluated in a sound-treated booth. HPS was superior for speech in noise in a reverberant environment. Future research should focus on modifications to non sound-treated environments for telehealth service delivery in rural areas.

Keywords

cochlear implants; telehealth; telepractice; speech perception; Polycom

INTRODUCTION

With technological advances in cochlear implants (CIs) and expanding candidacy criteria over the last two decades, a significant number of CI recipients achieve open-set speech perception (Battmer, Reid, & Lenarz, 1997; Parkinson et al., 2002; Gifford, Dorman, Shallop, & Sydlowski, 2010). Speech perception can be evaluated using a wide range of stimuli in quiet and in noise to track progress over time. Speech-perception testing is a routine part of clinical CI recipient appointments and is typically performed in a sound-treated booth using calibrated speech material at a pre-determined sound pressure level (SPL; Luxford et al., 2001; Gifford, Shallop, & Peterson, 2008). CI recipients may undergo speech-perception testing, in addition to other programming and objective tests 6–10 times within the first year of device use, with additional testing required annually for monitoring progress with the CI. As with most specialty areas in health care, clinical CI programs are often located in more densely populated regions; therefore, the ability to return for necessary follow-up appointments can be challenging for CI recipients who live far from a CI center.

Telehealth services may be more feasible and cost effective for patients who live a significant distance from the CI center.

Telehealth services have become more widespread in recent years, allowing the remote exchange of health information across various disciplines including medicine, psychiatry, dentistry, and speech pathology/audiology (American Speech-Language-Hearing Association, 2005; Geoffroy et al., 2008; Friction & Chen, 2009; Reynolds, Vick, & Haak, 2009). Telehealth services have primarily been provided using the internet and/or videoconferencing technology to extend health services, as well as non-clinical information such as research and education, to geographical areas where needed services may be limited (De Las Cuevas, Arredondo, Cabrera, Sulzenbacher, & Meise, 2006; Bickett-Weddle, Aquilino, & Roth, 2008). As with any interactive technology, and especially when disseminating protected health information across the internet, it is essential to utilize technology that meets clinical service delivery standards. As the use of telehealth becomes more prevalent, evidence from research is needed to set minimal guidelines for the appropriate use of this technology and to quantify the impact of technology and remote locations on the quality of services provided.

Telehealth for CI recipients has been successfully applied to intraoperative testing (Shapiro, Huang, Shaw, Roland, & Lalwani, 2008), programming (Ramos et al., 2009; McElveen et al., 2010), and objective tests (Hughes et al., in press); however, research investigating speech perception via telehealth has revealed additional challenges (Hughes et al., in press). Because speech perception scores are used to track progress in CI recipients, accurate and consistent administration is necessary in order for telehealth to be used routinely for service delivery. It is also important to evaluate speech perception using materials that are used in a clinical setting, which include a variety of stimuli such as monosyllabic words, sentences in quiet, and sentences in noise.

Ribera (2005) evaluated the remote use of the Hearing in Noise Test (HINT) with normal hearing listeners using Meeting Point (version 4.6 software) and ViGO videoconferencing. Results revealed that administration and scoring of the HINT via a remote connection was equivalent to face-to-face administration and scoring. Although the study results revealed the remote application of the HINT is acceptable, it was performed with normal-hearing listeners seated in a sound-treated booth. Acoustic differences between sound-treated booths and alternative test environments (office setting, with less stringent requirements for noise and reverberation) could have a much larger impact on listeners with a CI, affecting the consistency of results obtained in the same setting and comparability of results across different settings.

McElveen et al. (2010) and Ramos et al. (2009) evaluated speech perception in CI recipients using maps created over a remote connection compared to maps made in the traditional face-to-face condition. In the McElveen et al. (2010) study, there was no significant difference in Consonant-Nucleus-Consonant (CNC) and HINT scores across the two mapping applications. Ramos et al. (2009) also found no significant differences in performance on disyllabic word scores in their study. In both studies, however, speech-perception testing was performed in the standard face-to-face setting after a remote-mapping session, not over an internet or videoconference connection at a remote location. These studies have demonstrated that creating CI maps over the internet equates to similar speech-perception outcomes as maps made in a standard face-to-face manner. However, it is necessary to determine whether all CI measures, including speech perception, can be administered via telepractice for consistent and comparable documentation of outcomes with the CI. Because a wide range of speech materials are used to assess speech recognition with CI recipients,

investigating remote applications of the HINT and other speech stimuli with varying amounts of linguistic content is important.

In a study conducted by Hughes et al. (in press), a comprehensive set of CI measures were conducted using Polycom (Clary Business Machines Co., Pleasanton, California, USA) videoconferencing and a secure socket layer virtual private network (SSLVPN) using an ABA study design. CI measures of map levels, electrode impedance, psychophysical thresholds, and ECAPs were equivalent across test settings (remote vs. face-to-face). However, speech perception in quiet and in noise was poorer when using the Polycom videoconference technology in a non-sound-treated room at the remote site compared with the traditional face-to-face condition in a sound booth. It was unclear whether speech-perception scores were poorer in the remote condition because (1) speech-perception materials were transmitted over a videoconference link from the experimenter site, which may have negatively affected the speech signal provided to the recipient at the remote end (e.g. limited transmission quality, internet bandwidth, and compressed audio); (2) ambient noise and reverberation were higher at the remote site due to non-standard test environments; or (3) a combination of both equipment and environment effects. It is important to investigate these differences before speech-perception testing can routinely be used for telepractice with CI recipients. The present study aimed to investigate the relative contribution of equipment and environment on speech perception tested in the remote condition for individuals with CIs.

One standard to help guide acceptable test conditions for remote applications is the American National Standard Institute for Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms (ANSI S3.1-1999). ANSI advises that audiometric test rooms meet specific sound pressure levels in order to permit testing to 0 dB hearing threshold level (HL) (ANSI S3.1-1999). These standards include maximum allowable sound pressure levels at octave frequencies from 125 Hz to 8000 Hz; however ANSI does not specify allowable sound pressure levels for speech-perception testing. Excessive room noise and reverberation have been shown to negatively affect speech perception, especially for individuals with hearing loss (Beutelmann & Brand, 2006; Poissant, Whitmal, & Freyman, 2006). Unfortunately, sound-treated spaces are usually not available in rural communities where speech-perception testing may be conducted via remote methods. Investigating the most favorable testing configuration may help optimize speech-perception testing in conditions where sound-treated booths are not accessible.

Finally, little is known about the perceptual effects of transmitting speech through the internet or videoconferencing equipment for CI recipients or other individuals with hearing loss. Ribera (2005) suggested that transmitting speech material over a network does not comprise the signal presented to listeners at the remote end; however, subjects in that study had normal hearing and were seated in an acoustically controlled sound booth. It is unclear whether results would be similar for CI recipients using videoconferencing technology. Videoconferencing technologies are limited by the amount of audio information they can transmit over Internet Protocol (IP) bandwidth restrictions (Polycom VSX 7000 Product Reference Guide, 2003, page 14). Due to bandwidth limitations, audio information presented through a videoconference link is first compressed (encoded) to reduce the used bandwidth for delivery to the recipient site. At the recipient site, the signal is then decoded before introduction to the listener. Several factors may affect the signal during this process including limited frequency response of the system (human ear is 20 Hz – 22 kHz; most technologies have more limited bandwidth), low bit rates, muting or interruption of sound, artifacts from noise sources, and packet (data) loss from compression (Orto & Karapetkov, 2011; Ribera, 2005). These factors may affect the acoustic representation of the signal for the listener at the remote end, likely resulting in either a delay or distortion of the signal.

Acoustic degradation related to the transmission system or processing may have an even more detrimental impact on listeners with a CI, because they are listening with a compromised auditory system. More information is needed regarding audio transmission with Polycom and other telehealth technologies to determine the effect on speech perception for CI recipients.

The objective of this study was to evaluate systems for telehealth administration of speech-perception stimuli to CI recipients at a far-site location as well as differences in test environments. The literature suggests that testing system, environment, or both may have a negative effect on CI recipients' performance in the remote condition (Hughes et al., in press; Ribera, 2005). Because differences in performance may necessitate a standard for clinical telehealth services, these effects should be explored. The first goal of this study was to evaluate two different systems for administration of speech-perception materials to a remote location. Previous research suggested that Polycom with visual concert (PVC) transmission may negatively affect a speech signal (Hughes et al., in press); therefore a custom-made hybrid presentation system (HPS) was designed for the present study to eliminate bandwidth restrictions by presenting speech stimuli directly from a speaker at the subject location.

The second goal of the study was to evaluate the effect of testing room environment (quiet office vs. sound-treated booth). Hughes et al. (in press) suggested that remote-site speech-perception scores in that study may have been negatively affected by ambient noise and reverberation from testing in a non-sound-treated room. CI recipients were evaluated using a range of stimuli including monosyllabic words, sentences in quiet, and sentences in noise; therefore, this evaluation will provide valuable information for telehealth service delivery. Speech perception was evaluated in four different conditions to assess the effects of system and environment: (1) PVC in a sound-treated booth, (2) HPS in a sound-treated booth, (3) PVC in a quiet office, and (4) HPS in a quiet office.

It was the objective to evaluate speech perception in conditions that would be hypothetically the most ideal (HPS in a sound booth) versus the most realistic for telehealth applications (PVC in a quiet office). It was hypothesized that CI recipients' speech-perception scores across all measures would be best in the HPS + sound booth condition because this represents the quietest environment with no audio compression or bandwidth restrictions. Stimuli of varying linguistic complexity from monosyllabic words to sentences in noise were used to evaluate the effect of these variables across a continuum of stimuli that would be used clinically with CI recipients. The results of this study were compared to results from the same group of subjects who participated in the study by Hughes et al. (in press) in order to investigate discrepancies between speech-perception results and remote environments used for testing in that study.

METHODS

Subjects

Sixteen adult and pediatric subjects participated in this study (14 unilateral & 2 bilateral CI recipients; mean age: 48 years; range: 12–87 years). Demographic information for each subject is outlined in Table 1. All subject recruitment and informed consent were performed by personnel from the Boys Town National Research Hospital (BTRNH) Cochlear Implant Research Laboratory. The goal was to enroll subjects with at least one year of experience with the CI before participating in the study; however, one subject had only 5 months of device use (mean duration of use: 6 years; range: 5 months–14 years). All subjects except F1/R3 (this was a single bilaterally-implanted subject; subject numbers are designated on a

per-implant basis) also participated in the Hughes et al. (in press) study. This study was approved by the BTNRH Institutional Review Board under protocol 03-07-XP.

Equipment Set-up

Testing was performed at BTNRH with the subject in the CI laboratory and the experimenter in a small conference room on a separate floor. Each subject participated in four listening conditions, which are described below. For all conditions, a Polycom unit using a pod microphone with table-top placement was used for bi-directional video and audio communication between the subject and experimenter. A Polycom Video Station Experience (VSX) 7000 was used in the conference room with the experimenter while a Polycom High Definition Experience (HDX) 7000 was used at the subject location to allow communication between the subject and the experimenter at all times.

Figure 1 illustrates the two systems evaluated in this study. The first system (Fig. 1, top), also used by Hughes et al. (in press), was a Polycom VSX/HDX 7000 with a visual concert (PVC). A visual concert is an interface that allows users to connect a computer to a Polycom system in order to present high-resolution graphics and audio presentations from a media player (e.g. computer, DVD player) to listeners at a far site. Before the subject arrived, a direct call (like making a telephone call) was made from the subject's Polycom unit to the experimenter's Polycom. The two Polycom systems were connected using a dedicated web-streaming and videoconferencing network with an encrypted 3-megabytes per second (mbps) bandwidth; therefore, all testing was conducted over a secure connection. The visual concert, connected to a Latitude D630 laptop computer and the Polycom at the experimenter location, allowed for the direct introduction of speech material (.wav files) across the dedicated network to the Polycom speakers at the subject site (bypassing the tabletop microphone). Using a 512-kbps call rate, speech stimuli were transmitted across the videoconference link to the subject location. Stimuli were presented at the subject location using Mitsubishi SP-322V speakers that accompanied the Mitsubishi display monitor for the Polycom system (Mitsubishi Electric Corporation; Tokyo, Japan).

Polycom technology is a widely-available product used for videoconferencing. As stated above, however, it transmits video and audio information in a compressed format. Video content for this study (for communication purposes only) was transmitted at a dimension of 1024×768 kbps. Transmission of the speech stimuli was performed with the Polycom Siren™ 14/G 722.1C technology. This is a standard wideband audio compression algorithm with an upper frequency range of 14 kHz, transmitted at bit rates of 24–48 kbps (Polycom VSX 7000 Product Reference Guide; page, 14). It should be noted that because this study was performed over a dedicated network, it avoided most internet traffic that may occur over other existing connections (e.g. a bridge network shared by many sites causing additional internet bandwidth limitations and loss of signal information during transmission). Therefore, PVC in this study likely reflects the “best-case scenario” for the administration of speech-perception materials to CI recipients using available Polycom videoconferencing technology.

The second system evaluated was a custom-made hybrid presentation system (HPS) (Fig. 1, bottom) which was designed to eliminate bandwidth and compression issues associated with the transfer of speech materials across a videoconference/network link. With HPS, custom software installed on laptops at both the experimenter and subject sites allowed for speech materials to be played directly from a high-quality speaker at the subject location. This application allowed the experimenter (in the conference room) to control/command the software at the subject site, using an internet connection. The stimulus-delivery application was developed within the interactive sound synthesis and processing language Max/MSP (Cycling '74; San Francisco, CA). The transfer of commands, including stimulus choice,

playback volume, and transport (play, stop) configuration from the experimenter to subject software was accomplished with Open Sound Control (OSC; Wright, 2005; Berkeley, CA). OSC is used for interactive control over existing high-speed networking technologies (not limited by a local internet system). OSC is a binary format that transfers packets of data that the experimenter and subject programs can decode using User Datagram Protocol (UDP). In order to accomplish this, the two computers were linked to each other using a dedicated send-and-receive network port. The experimenter's computer was used to control the subject's computer, allowing the experimenter to select and play speech material using uncompressed 16-bit .wav files that resided on the computer's internal hard drive at the subject location. Finally, the .wav files were converted to the analog domain by means of a dedicated digital audio convertor (E-MU 0202 USB; E-MU Creative, Milpitas, CA) and then played back through a Focal CMS 40 nearfield studio speaker (Focal – JM Lab Company, Saint-Jean-Bonnefonds, France). This allowed the speech material to be played directly from the Focal speaker at the subject site, eliminating transmission of the material over an internet or videoconference link.

Acoustical Measurements

Speech perception was tested in two environments: a sound-treated audiometric booth and an office. The background noise and reverberation characteristics of both environments were evaluated in order to determine the effect of testing environment on speech perception. As stated, a sound-treated booth is typically used for clinical assessment of speech perception, whereas an office setting is more typical of the environment that would be available for remote testing.

A single set of octave-band background noise measurements were made in the two listening conditions (quiet office and sound-treated booth). Measurements, taken with a Type I integrating sound-level meter (Larson Davis, model 824; PCB Piezotronics, Inc, Depew, NY), included octave bands from 125 Hz to 8000 Hz and 5-min L_{eq} broadband noise, which is the average (over a five-minute period) A-weighted SPL in each environment. The office was a 9' × 7' room with a 12' ceiling; it contained a desk spanning two walls, overhead cabinets, a storage closet, and carpeting (no windows). Noise sources included a desktop PC, laser-printer, overhead lights, and fluorescent strip desk lighting. The office was located within the Cochlear Implant Research Laboratory; therefore, hallway traffic was not an issue. Acoustical measurements in the office were taken at a quiet time during the day when the external airborne and impact noise could be minimized. For all subsequent measurements and experimental testing, the internal noise sources that could be eliminated in the office (i.e. computer, printer, overhead lights) were turned off excluding the fluorescent strip lights which were kept on during testing. These measurements thus represent the best-case scenario for ambient background noise in a quiet office. The single-walled sound-treated booth was adjacent to the office used in this study. It measured 9' × 9' with a 6' 7" ceiling. The booth contained a table, recliner chair, and large television (not used in this study). The doors to the sound booth and office were closed during testing and calibration.

In addition to octave-band background noise measurements, measurements of reverberation time (T_{30}), early decay time (EDT), and clarity of speech (C_{50}) were conducted in the test environments because excessive reverberation has been shown to affect speech intelligibility in rooms (Bradley, 1986; Davis & Davis, 1997). T_{30} is the time required in seconds for a sound to decay (or decrease in level) by 60 dB after the sound source has stopped (smaller T_{30} is more favorable). EDT represents the decay time for the first 10 dB of the T_{30} value (faster is better). C_{50} is a measurement of speech clarity in dB determined by measuring the ratio of energy in the first 50 msec to the energy arriving after 50 msec, thus measuring the prominence of the direct sound within a reverberant environment. The higher the dB value,

the clearer the speech signal will sound amongst the reverberation. Because speech perception was of primary concern in the current experiment, and the ratio of early-to-late energy is known to affect speech intelligibility (Bistafa & Bradley, 2000), C_{50} was used because it is a good correlate to the effects of room acoustics on the intelligibility of speech (Bradley, Reich, Norcross, 1999).

Measurements were conducted by obtaining monaural impulse responses (IRs) in each space. IRs were measured using a 50-second logarithmic sinusoid-sweep excitation signal with a 24-bit resolution analog-digital (A/D) conversion and 48-kHz sampling rate. In order to generate the impulse, the recorded sweep was convolved in the time domain using an appropriate time-inverse filter with a -6 dB/octave equalization to compensate for the logarithmic frequency-time spacing of the excitation signal. This method is described by Farina (2000) and allows for the recording of IRs with a very high signal-to-noise ratio (SNR). A single loudspeaker (Focal, CMS-40) served as the sound source and a small-diaphragm measurement microphone (Earthworks, M23; Milford, NH) was used. EDT and T_{30} were calculated from the IRs in accordance with ISO 3382 (1997).

Procedures

Each subject participated in speech-perception testing in four listening conditions while using his/her everyday speech-processor settings. Speech-perception measures consisted of one list of the CNC monosyllabic words in quiet (Peterson & Lehiste, 1962), two lists of the HINT measured in quiet (Nilsson, Soli & Sullivan, 1994), and two lists of the Bamford-Kowal-Bench Sentences-In-Noise (BKB-SIN; Bench, Kowal, & Bamford, 1979; re-recorded in American English by Etymotic Research, Inc., 2005) per listening condition. Sentence lists were presented in a randomized order, not repeated across any of the four listening conditions, and the pairing recommendations for the CNC and BKB-SIN were used to ensure equivalency across test conditions (Skinner et al., 2006; Etymotic Research, Inc., 2005).

Calibration of the speech-perception materials was performed for both PVC and HPS outputs using a Radio Shack sound level meter. All tests were administered at 60 dB SPL (A). The subject was instructed to repeat what he/she heard and to take a guess if unsure. Subjects' responses were scored by the experimenter observing via the Polycom link. The subject could view the experimenter at all times through the Polycom videoconference link. The four listening conditions described below were performed in a randomized order. Testing was performed in one day (approximately 2 hours) and breaks were provided to the subject during the set-up and calibration of each condition (about 15 minutes).

1. *PVC in the quiet office.* For this condition, the subject was in the office described above. The subject was seated approximately 1 meter from the speaker of the Polycom unit. Speech materials were administered from the Polycom 7000 VSX with visual concert at the experimenter site (in the conference room) using the dedicated network port to the Polycom 7000 HDX speakers at the subject's location. This condition is similar to the speech-perception testing that was conducted by Hughes et al. (in press), in which speech perception was tested in a non-sound-treated room using PVC transmission to a remote site.
2. *PVC in the sound-treated booth.* This condition was administered in the same manner as PVC in the quiet office described above; however, subjects were seated in an acoustically controlled sound booth rather than the office. For ease of testing at the subject location, the Polycom system, Focal speaker, computer for HPS playback requirements, and video recorder were mounted on an AnthroCart^R (Tualatin, Oregon) specifically designed for this study. The cart was transported to the sound booth or office depending on the test order.

3. *HPS in the quiet office.* The Polycom system was used only for communication between the subject and the experimenter, while the HPS custom-made program was used to play the speech stimuli from the Focal speaker at the subject location. During administration of the tests, the Polycom tabletop microphone at the experimenter site was muted to eliminate the introduction of unwanted background noise to the subject. The subject was seated approximately 1 meter from the Focal speaker.
4. *HPS in the sound-treated booth.* Testing was conducted using HPS administration of speech stimuli to subjects seated in an acoustically controlled sound booth 1 meter from the Focal speaker.

RESULTS

Acoustical Measurements

Figure 2 displays the broadband acoustical measurements for the sound-treated booth and quiet office (external noise sources “off”); also included is an average (± 1 SD) of the octave-band measurements from the three remote sites¹ used in Hughes et al. (in press; referred to as “remote avg” on the graph). This comparison was performed in order to determine whether differences existed between the testing environments in the current study and Hughes et al. (in press). A Kruskal-Wallis One-Way Analysis of Variance (ANOVA) revealed a significant difference in octave-band noise between the testing sites ($H = 11.29$, d. f. = 2, $p = 0.004$). A Pairwise Multiple Comparison (Dunn’s Method) revealed significantly higher noise levels for the quiet office than the sound booth ($p < 0.05$). Octave-band noise levels were also significantly higher for the average of the three remote sites from Hughes et al. (in press) compared to the sound booth ($p < 0.05$). The office environment was not significantly different than the remote sites from Hughes et al. (in press). The octave-band background noise for only the sound booth was below the recommendations of ANSI S3.1 (1999) for all frequencies used for audiometric testing.

Figure 2 also illustrates the L_{eq} 5-minute measurements for the current study and remote average (± 1 SD) from Hughes et al. (in press). In the quiet office, with all noise sources (computer, printer, lights) turned “on,” the environment measured 42.1 dB (A). When the noise sources (except for the fluorescent strip lighting) were eliminated, the L_{eq} was reduced by 10.4 dB to 31.7 dB (A). L_{eq} for the sound-treated booth was 27.8 dB (A), 3.9 dB quieter than the “all off” L_{eq} for the office setting. The average L_{eq} for the remote sites in Hughes et al. (in press) was 43.2 dB (A), which was most similar to the office “all on” condition. There is no standard to compare these measurements to; however, speech materials were presented at 60 dB SPL (A) which was approximately 28 dB SPL above the office “all off” measurement (31.7 dB (A); recall that testing was conducted in the “all off” condition).

Figure 3 shows the reverberation results for the sound booth, office, and remote average (± 1 SD) from Hughes et al. (in press). Only T_{30} is included from Hughes et al. (in press) as that study did not evaluate C_{50} or EDT. One-Way ANOVA results evaluating T_{30} across the three environments revealed a statistically significant difference in reverberation time ($F = 49.31$, d. f. = 2, $p < 0.001$). A Pairwise Multiple Comparison (Holm-Sidak) indicated that T_{30} was significantly higher for the office (i.e., more reverberant) than the sound booth ($p < 0.001$), higher for the remote sites compared to the sound booth ($p < 0.001$), and higher for the remote sites compared to the office ($p < 0.001$). One-way ANOVA results revealed a statistically significant effect of room for EDT ($H = 9.89$, d.f. = 1, $p < 0.001$) and C_{50} ($H =$

¹In Hughes et al. (in press), subjects visited one of three remote testing sites closest to their home. Rooms at the remote sites were small conference rooms equipped with videoconferencing technology, not sound-treated booths.

9.80, d.f. = 1, $p < 0.001$) for the current study. Post-hoc analyses (Dunn's Method) showed a significantly higher C_{50} value for the sound booth than the office ($p < 0.05$) as well a longer EDT in the office compared to the sound booth ($p < 0.05$). As expected, the sound booth was a quieter and less reverberant space than the office setting. Even though noise sources were eliminated for optimal listening in the office, T_{30} , C_{50} and EDT results indicate that the sound booth was much more favorable for speech understanding.

Speech Perception

Figure 4 shows mean results (± 1 SD) across the four listening conditions (two systems and two environments) for the four speech-perception measures in the current study. For all statistical analyses involving speech-perception data, differences between recognition of CNC words and CNC phonemes were analyzed using a repeated-measures multivariate analysis of variance (MANOVA), because word and phoneme scores were derived from the same task and were not independent observations. Results for CNC words and HINT sentences were analyzed separately from BKB-SIN sentences because the former were measures of percent correct in quiet, while the BKB-SIN sentences were measured in noise using an adaptive paradigm to determine the SNR for 50%-correct recognition.

The overall effect of test environment (quiet office vs. sound-treated booth) on recognition of CNC words and phonemes was significant [$F(2,14) = 13.719$, $p = 0.001$, Wilks' $\lambda = 0.338$, $\eta^2_p = 0.662$]. The effect of system (PVC vs. HPS) on CNC words and phonemes was not significant [$F(2,14) = 2.381$, $p = 0.129$, Wilks' $\lambda = 0.746$, $\eta^2_p = 0.254$], reflecting no difference in CNC word or CNC phoneme recognition between PVC and HPS systems. Further analysis of the effect of environment on words and phonemes indicated that the effect of room was significant for recognition of both CNC words [$F(1,15) = 25.142$, $p < 0.001$, $\eta^2_p = 0.626$] and CNC phonemes [$F(1,15) = 28.725$, $p < 0.001$, $\eta^2_p = 0.657$]. Specifically, CNC word and phoneme recognition were both higher (better) in the sound-treated booth than in the office.

The effect of environment and system on HINT sentences in quiet and BKB sentences in noise was assessed using ANOVA. For HINT sentences in quiet, the effect of environment was significant [$F(1,15) = 8.96$, $p = 0.009$, $\eta^2_p = 0.374$], with better sentence recognition in the sound-treated booth than in the office. The effect of system [$F(1,15) = 0.603$, $p = 0.449$, $\eta^2_p = 0.039$] and two-way interaction between system and test environment [$F(1,15) = 0.435$, $p = 0.520$, $\eta^2_p = 0.028$] were not significant, suggesting that system did not impact HINT sentence recognition and that the main effect of environment was observed for both systems, respectively.

For BKB sentences in noise, the two-way interaction between environment and system was significant [$F(1,15) = 22.563$, $p = 0.002$, $\eta^2_p = 0.469$], indicating that the pattern of BKB sentence recognition in noise for each test environment was dependent on the system. Specifically, there was no difference between PVC and HPS systems in the sound-treated booth, but BKB sentence recognition in noise was significantly better (lower SNR) for HPS in the office than for PVC in the office (2.1 dB difference). Results for the BKB-SIN with HPS in the office (10.5 dB) were not significantly different from either presentation system in the sound-treated booth (10.2 dB for PVC and 10.6 dB for HPS). Results suggest that PVC in the office yielded the poorest results for speech in noise testing.

It was of interest to analyze performance differences between the testing environments in the current study and Hughes et al. (in press). Recall that it was unclear whether test system or environment yielded poorer speech-perception results in the earlier study. While the Hughes et al. study utilized conference rooms for testing (with no modifications), the testing environment in the current study was an office with noise sources minimized as much as

possible and a sound-treated booth. To facilitate a comparison between the speech-perception results from Hughes et al. and the current study, speech perception was analyzed from a subset of 14 subjects that participated in both studies. Subjects not included in this comparison were R3/F1, because that subject did not participate in Hughes et al., and F10/F11, who was tested with bilateral CIs in the present study but was only tested with a single CI in Hughes et al. Two measures were made at the remote visit in Hughes et al. using PVC; the average of the two measures was used for the comparisons made here. From the present study, scores from PVC in the office and PVC in the sound-treated booth were used to compare to the average of the two remote PVC scores from Hughes et al. PVC was used for the comparison because only that system was used for both studies.

In order to analyze the effect of environment on speech perception, three analyses were completed for PVC data for the remote site (Hughes et al., in press), PVC in the sound-treated booth (current study), and PVC in the quiet office (current study). Results are displayed in Figure 5. Overall, there was a significant effect of environment on the CNC scores [$F(4,52) = 15.317$, $p < 0.001$, Wilks' $\lambda = 0.202$, $\eta^2_p = 0.551$]. Further analysis of each dependent variable revealed significant effects of environment on scores for both CNC words [$F(2,26) = 11.283$, $p = 0.001$, $\eta^2_p = 0.465$] and CNC phonemes [$F(2,26) = 24.792$, $p < 0.001$, $\eta^2_p = 0.656$]. To examine the pattern of significant differences across locations while controlling for Type I error rate, post-hoc comparisons were completed using Fisher's Least Significant Difference (LSD). Post-hoc results revealed significantly higher CNC word and phoneme recognition for PVC in the sound-treated booth (63% word, 79% phoneme; $p < .001$ vs. remote words and phonemes) and office (56% word, 76% phoneme; $p < .001$ vs. remote words and phonemes) than at the remote sites (48.2% word, 69.5% phoneme). The differences between sound-treated booth and office were not significant for CNC words or phonemes. The effect of location on HINT sentences in quiet was assessed using a repeated-measures ANOVA. The main effect of location was significant [$F(2,26) = 19.033$, $p < 0.001$, $\eta^2_p = 0.594$]. Post-hoc testing revealed no significant difference between sound-treated booth and office, with both conditions resulting in significantly higher speech perception than the remote sites used in Hughes et al. (in press).

The effect of location on BKB- SIN results (Fig. 5, bottom right) was tested using a repeated-measures ANOVA. The main effect for location was significant [$F(2,26) = 9.016$, $p = 0.001$, $\eta^2_p = 0.410$]. Post hoc testing revealed that sentence recognition in noise was better (lower SNR) for the sound booth than for the quiet office ($p < 0.001$) or remote sites ($p < 0.001$), which were not significantly different from each other ($p = 0.312$). Overall, the effect of location on speech recognition with the PVC system was consistent across stimulus type and varied depending on whether the task was completed with or without the addition of competing noise. For speech perception in ambient acoustic conditions, both the sound-treated booth and office resulted in higher performance than the remote sites used in the earlier study, whereas for speech recognition with the addition of multi-talker babble, the sound-treated booth was superior to both the office and remote sites.

DISCUSSION

Research has determined that traditional CI measures such as electrode impedance, programming, and ECAP testing can be conducted via telehealth with equivalent results as a standard face-to-face appointment (Ramos et al., 2009; McElveen, et al., 2010; Hughes et al., in press). However, our previous investigation of telehealth with CI recipients revealed poorer speech perception in the remote condition (Hughes et al., in press). The goal of the present study was to investigate whether poorer speech-perception scores were due to bandwidth problems associated with the type of system used to transmit speech stimuli over

the internet or the acoustic environment used for testing (or a combination of both). Testing was conducted for a variety of speech stimuli in quiet and in noise.

The current study's results reveal no significant effect of system (PVC or HPS) when subjects were tested on speech in quiet (CNCs and HINTs). When tested on these same stimuli, subjects performed best in the sound booth compared to the quiet office (Fig. 4). Background and reverberation measurements support these findings. The sound booth was a quieter, less reverberant space that resulted in better speech perception scores compared to the office environment. Even when efforts were made to eliminate background noise in the office, CI recipients still experienced a decrease in speech perception compared to performance in the sound booth.

For testing in the presence of background noise (BKB-SIN), results indicated that a combination of system and environment may be a significant determinant of subjects' performance (Fig. 4). When in the office (a more reverberant environment), subjects performed more poorly with PVC transmission of the speech stimuli (a decrease in performance of 2 dB) compared to HPS. In the sound booth, however, there was no significant difference in performance using either system. A 2-dB difference can have a large impact on speech recognition in noise; this difference indicated that subjects may have been more sensitive to changes in the signal-to-noise ratio when testing was performed with the PVC in the office compared to HPS in the office. It is likely that a combination of reverberation and background noise as well as compression and bandwidth limits from the PVC were more detrimental than testing with the background noise alone (as in the HPS condition). This result suggests that HPS may be a superior system to use for remote testing, at least when testing speech in noise in reverberant environments.

Comparison of this study to Hughes et al. (in press) reveals similar findings related to the effects of testing environment. Speech perception with PVC transmission was compared for a subset of subjects participating in both studies (Fig. 5). Subjects performed best in the sound booth for all speech measures, as expected. For testing in quiet (CNCs and HINTs), scores for the remote sites in Hughes et al. (in press) were significantly poorer than both the sound booth and office, while there was not a significant difference in scores between the sound-treated booth and office. Recall that in the current studies' analysis, however, speech perception in quiet was significantly better for the sound-treated booth than quiet office. Although the magnitude of the difference in speech perception between the sound-treated booth and office did not change (6% higher on average in sound-treated booth), the additional comparison of results from Hughes et al. (2011) resulted in a non-significant difference between sound-treated booth and quiet office for the PVC subset. This was because a larger difference was needed to reach statistical significance for the larger number of factors that were being compared.

When comparing speech in noise (BKB-SIN) results for the two studies, the trend in subjects' scores was similar to testing in quiet with the best performance (lower SNR) for the sound booth and poorest performance (higher SNR) for testing at the remote sites in Hughes et al. (in press). Results revealed that scores were significantly better for the sound booth compared to the office as well as the sound booth compared to the remote sites; however, performance in the office in the current study was not significantly different than performance at the remote sites. It is likely that a combination of reverberation and fluctuating ambient environment noise (heating and ventilating systems, hallway traffic, etc) made both the office and remote sites equally challenging listening environments, especially for speech in noise testing because the signal-to-noise ratio was effectively higher than for the sound booth.

Results from the current study and Hughes et al. (in press) reveal that the sound booth provided the most optimal environment for testing, as expected. As discussed, sound-treated booths are not typically available in rural communities. In an effort to evaluate spaces that are available in rural areas, this study analyzed speech-perception scores in three different test environments: a sound-treated booth, a quiet office, and remote sites without any noise modifications. Results determined that speech perception scores do improve when noise sources can be eliminated in a testing suite (see Fig. 5); however, this modification alone is not enough to provide an adequately controlled environment for scores that are equal to those obtained in a sound booth. Results of the current study do suggest that HPS, when used for speech-in-noise testing, may help eliminate the negative effects of background noise.

Recall that the HPS was designed to eliminate the transfer of speech material across a videoconference link. Our previous investigation of speech perception through telehealth suggested that Polycom technology may have negatively affected speech presented to CI listeners at remote sites (Hughes et al., in press). With Polycom, audio information is compressed before being sent to a user at a far-site location; therefore, it was hypothesized that HPS would be superior technology for testing by eliminating this transfer. There was however, no difference in speech-perception scores for testing conducted in quiet for HPS or PVC. It appears that HPS was only superior when used for testing speech in noise in a reverberant environment. The reader should keep in mind that testing with the PVC in the current study was done through a dedicated network, which likely reduced internet traffic and muting, loss of sound, or packet loss that would traditionally be experienced over busier open networks with PVC. The dedicated network may have provided an avenue for less compression of the speech stimuli in this study. A dedicated network was not used in the earlier study; which may have contributed to the poorer results (in addition to the increased reverberation and background noise at the testing sites). The HPS system was superior for testing in noise and could easily be used across any internet network system. However, it is not a commercially-available system, and would require user set-up, which may be difficult without a prerequisite background using these technologies. PVC is commercially available and more user friendly, although it can be expensive to purchase. In our previous investigation, Polycom systems were readily available at rural health centers and Universities in the states of Nebraska and South Dakota (Hughes et al., in press).

Another alternative to investigate for testing speech perception for telehealth purposes is direct administration of a speech stimulus to the recipient's speech processor (direct connect). Ideal administration would be through the manufacturer software, eliminating the need for additional equipment and software at a remote site. Direct administration of speech stimuli is currently not available for commercial use in the United States. This approach could (1) potentially bypass the background noise and reverberation in the environment, and (2) prevent the need for a sound booth in rural communities. This option, however, is limited in clinical utility because the microphone functionality and front-end processing would not be assessed with this approach. Direct administration is less representative of real-life listening than acoustic presentation of speech as through traditional test methods although it could be argued that traditional test methods (i.e. in the sound booth) are also not representative of real-world listening conditions.

The test-retest reliability of speech-perception scores obtained in a non-sound-treated clinical space may be worth investigating. The purpose of testing in a sound booth is to have a quiet and controlled environment for speech-perception scores to be compared and monitored over time and potentially even across clinics. Often testing is performed with pre-recorded stimuli or in the presence of background noise in an attempt to recreate more realistic listening environments, particularly when CI recipients' scores are reaching ceiling

levels in quiet or patients report difficulties hearing in “real-world” situations. However, if testing could be performed in a clinical space while monitoring and controlling fluctuating noise sources (i.e. electronics, lights, and heating/air conditioning units), such as in this study, clinical spaces could function as a more realistic test environment. Regular clinic rooms could then be utilized for telehealth administration of speech perception stimuli, as long as the effects of background noise and reverberation in the environment are considered. Further research investigating modifications to clinical spaces in remote areas including the use of acoustical modifications to reduce reverberation and background noise may lead to scores equivalent to those obtained in a sound booth.

Finally, it is worth investigating the appropriateness of traditional clinical testing methods where CI recipients are seated directly in front of a speaker in a sound-treated booth. While sound booths provide a consistent environment across sessions for monitoring progress and outcomes with the CI, the resulting test scores are often inflated compared with subjective reports of performance in real life. Previous research has determined that listeners perform more poorly with lower signal-to-noise ratios and softer presentation levels (Firszt et al., 2004; McCreery et al., 2010). For CI recipients, a reduced signal-to-noise ratio and softer presentation level equates to even more difficulty in speech recognition and understanding. Perhaps modifications to standard testing protocols as suggested by Firszt et al. (2004) should be more strongly considered for clinical CI standards. A standard that incorporates considerations for face-to-face appointments as well as telehealth encounters would be ideal.

This study has expanded our knowledge regarding the feasibility of testing speech perception through telehealth with CI recipients. The variability of tests conducted outside of sound-treated booths should be quantified through further investigation. The use of acoustic treatments may also offer realistic options for creating an environment with characteristics that are equivalent to testing in the sound booth. Future research should focus on our ability to evaluate speech perception in telehealth applications with the same accuracy as a face-to-face visit. As technology for CIs continues to evolve, it is imperative that we expand our ability to reach patients and provide adequate and accessible clinical services to them. Telehealth is an efficient way to reach patients that have difficulty accessing clinical CI services.

Acknowledgments

This study was supported by the National Institutes of Health, National Institute on Deafness and Other Communication Disorders grant 3R01DC009595-01A1S1 and P30DC04662. The content of this project is solely the responsibility of the authors and does not necessarily represent the official views of the National Institute on Deafness and Other Communication Disorders or the National Institutes of Health. The authors thank Suman Barua and Jennifer Bournique for assistance with data collection, as well as the subjects for their time and participation.

References

- American Speech-Language-Hearing Association. Audiologists providing clinical services via telepractice. *ASHA Supplement*. 2005; 25:1–8.
- American National Standards Institute. ANSI S3.1–1999. Acoustical Society of America; Melville, NY: 1999. American National Standard for Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms.
- Battmer RD, Reid JM, Lenarz T. Performance in quiet and in noise with the Nucleus Spectra 22 and the Clarion CIS/CA cochlear implant devices. *Scandinavian Audiology*. 1997; 26:240–246. [PubMed: 9428033]
- Bench J, Kowal A, Bamford J. The BKB (Bamford-Kowal-Bench) sentence lists for partially-hearing children. *British Journal of Audiology*. 1979; 13:108–112. [PubMed: 486816]

- Beautelmann R, Brand T. Prediction of speech intelligibility in spatial noise and reverberation of normal-hearing and hearing-impaired listeners. *Journal of the Acoustical Society of America*. 2006; 120(1):331–342. [PubMed: 16875230]
- Bickett-Weddle DA, Aquilino ML, Roth JA. The cooperative University of Iowa/Iowa State University MPH program. *Journal of Veterinary Medical Education*. 2008; 35(2):173–176. [PubMed: 18723798]
- Bistafa SR, Bradley JS. Reverberation time and maximum background-noise level for classrooms from a comparative study of speech intelligibility metrics. *Journal of the Acoustical Society of America*. 2000; 107(2):861–875. [PubMed: 10687696]
- Bradley J. Predictors of speech intelligibility in rooms. *Journal of the Acoustical Society of America*. 1986; 80:837–845. [PubMed: 3760337]
- Bradley JS, Reich R, Norcross GN. A just noticeable difference in C50 for speech. *Applied Acoustics*. 1999; 58:99–108.
- Davis, D.; Davis, C. *Sound System Engineering*. 2. Burlington, MA: Focal Press; 1997. Speech recognition and information. Appendix 10; p. 639-644.
- De Las Cuevas C, Arredondo MT, Cabrera MF, Sulzenbacher H, Meise U. Randomized clinical trial of telepsychiatry through videoconference versus face-to-face conventional psychiatric treatment. *Telemedicine and e-Health*. 2006; 12(3):341–350. [PubMed: 16796502]
- Etymotic Research, Inc. BKB-SIN Test. Version 1.03. Elk Grove Village, IL: Etymotic Research, Inc; 2005.
- Farina, A. Simultaneous measurement of impulse response and distortion with a swept sine technique. Paper presented at the 108th Auditory Engineering Society Convention; Paris, France. 2000.
- Firszt JB, Holden LK, Skinner MW, Tobey EA, Peterson A, Gaggle W, Runge-Samuelson R, Wackym PA. Recognition of speech presented at soft to loud levels by adult cochlear implant recipients of three cochlear implant systems. *Ear & Hearing*. 2004; 25(4):375–387. [PubMed: 15292777]
- Friction J, Chen H. Using teledentistry to improve access to dental care for the underserved. *Dental Clinics of North America*. 2009; 53(3):537–548. [PubMed: 19482128]
- Geoffroy O, Acar P, Caillet D, Edmar A, Crepin D, Salvodelli M, Dulac Y, Paranon S. Videoconference pediatric and congenital cardiology consultations: a new application in telemedicine. *Archives of Cardiovascular Diseases*. 2008; 101(2):89–93. [PubMed: 18398392]
- Gifford RH, Shallop JK, Peterson AM. Speech recognition materials and ceiling effects: Considerations for cochlear implant programs. *Audiology & Neurotology*. 2008; 13:193–205. [PubMed: 18212519]
- Gifford RH, Dorman MF, Shallop JK, Sydlowski SA. Evidence for the expansion of adult cochlear implant candidacy. *Ear & Hearing*. 2010; 31:186–194. [PubMed: 20071994]
- Hughes ML, Goehring JL, Baudhuin JL, Diaz GR, Sanford T, Harpster R, Valente DL. Use of telehealth for research and clinical measures in cochlear implant recipients: A validation study. *Journal of Speech, Language, and Hearing Research*. (in press).
- ISO 3382. Acoustics — Measurement of the reverberation time of rooms with reference to other acoustic parameters. 1997.
- Luxford WM. the Ad Hoc Subcommittee of the Committee on Hearing and Equilibrium of the American Academy of Otolaryngology–Head and Neck Surgery. Minimum speech test battery for postlingually deafened adult cochlear implant patients. *Otolaryngology Head Neck Surgery*. 2001; 124:125–126.
- McElveen JT, Blackburn EL, Green JD, McLearn PW, Thimsen DJ, Wilson BS. Remote programming of cochlear implants: A telecommunications model. *Otology & Neurotology*. 2010; 31:1035–1040. [PubMed: 20147864]
- Nilsson M, Soli SD, Sullivan JA. Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. *Journal of the Acoustical Society of America*. 1994; 95:1085–1099. [PubMed: 8132902]
- Orto, C.; Karapetkov, S. Music performance and instruction over high-speed networks. White paper. 2011. Retrieved from http://www.polycom.com/products/telepresence_video/telepresence_solutions/personal_telepresence/cme_desktop.html

- Parkinson AJ, Arcaroli J, Staller SJ, Arndt PL, Cosgriff A, Ebinger K. The nucleus 24 contour cochlear implant system: adult clinical trial results. *Ear & Hearing*. 2002; 23(1 Suppl):41S–48S. [PubMed: 11883766]
- Peterson GE, Lehiste I. Revised CNC lists for auditory tests. *Journal of Speech, Language, & Hearing Disorders*. 1962; 27:62–70.
- Poissant SF, Whitmal NA, Freyman RL. Effects of reverberation and masking on speech intelligibility in cochlear implant simulations. *Journal of the Acoustical Society of America*. 2006; 119:1606–1615. [PubMed: 16583905]
- Polycom, Inc. Polycom VSX 7000 Product Reference Guide [Reference guide]. 2003. Retrieved October 3, 2011, from http://www.videotelco.com/docs/polycom/VSX%207000/vsx_prguide.pdf
- Ramos A, Rodriguez C, Martinez-Beneyto P, Perez D, Gault A, Falcon JC, Boyle P. Use of telemedicine in the remote programming of cochlear implants. *Acta Oto-Laryngologica*. 2009; 129:533–540. [PubMed: 18649152]
- Reynolds AL, Vick JL, Haak NJ. Telehealth applications in speech-language pathology: a modified narrative review. *Journal of Telemedicine and Telecare*. 2009; 15:310–316. [PubMed: 19720769]
- Ribera JE. Interjudge reliability and validation of telehealth applications of the hearing in noise test. *Seminars in Hearing*. 2005; 26(1):13–18.
- Shapiro WH, Huang T, Shaw T, Roland T, Lalwani AK. Remote intraoperative monitoring during cochlear implant surgery is feasible and efficient. *Otology & Neurotology*. 2008; 29:495–498. [PubMed: 18520584]
- Skinner MW, Holden LK, Fourakis MS, Hawks JW, Holden T, Arcaroli J, Hyde M. Evaluation of equivalency in two recordings of monosyllabic words. *Journal of the American Academy of Audiology*. 2006; 17:350–366. [PubMed: 16796301]
- Wright M. Open Sound Control: an enabling technology for musical networking. *Organised Sound*. 2005; 10:193–200.

Figure 1. Illustration of Polycom VSX/HDX 7000 (top) and Hybrid Presentation System (bottom) for the presentation of speech perception material from the experimenter to the subject site. VSX=video station experience, HDX=high definition experience.

Figure 2.

Octave-band measurements for the sound-treated booth, quiet office, average from three remote sites in Hughes et al. (in press) (± 1 SD), and ANSI S3.1-1999 recommendation for audiometric test rooms. L_{eq} 5 minute measurement results for the office with all noise sources on ("all on"), with noise sources off ("all off"), sound-treated booth, and average from remote sites (± 1 SD) in Hughes et al. (in press).

Figure 3. Reverberation measurements including reverberation time (T₃₀), early decay time (EDT), and clarity of speech (C₅₀). Top: T₃₀ and EDT (s) results from the current study and average T₃₀ from remote sites (± 1 SD) in Hughes et al. (in press). Bottom: C₅₀ (dB) results from the current study.

Figure 4.

Results for the four speech-perception measures in the four listening conditions for the current study. Asterisks denote significant differences across environments for a particular test system (horizontal brace) or across test system for a particular environment (vertical brace). Dashed and solid braces correspond with plots connected by dashed and solid lines, respectively. PVC=polycom with visual concert; HPS=hybrid presentation system.

Figure 5. Speech perception results for PVC by location for the current study and remote sites used in Hughes et al. (in press). Asterisks denotes significant differences across environments.

Table 1

Subject demographics.

Subj. #	Age (y)	Internal Device (s)	Ear	Processor(s)	Strategy, Per-Channel Rate (pps)	Dur. CI Use (y, m)
R10	69	Nucleus 24R (CS)	R	ESPrIt 3G	ACE, 1200	8, 5
R15	12	Nucleus 24R (CS)	R	Freedom	ACE, 900	14, 0
R3/F1	65	Nucleus 24R (CS)/24RE	R, L	Freedom, CP810	ACE, 900 (R & L)	9, 8/5, 6
F2	64	Nucleus 24RE	R	Freedom	ACE, 1200	3, 10
F5	51	Nucleus 24RE	R	Freedom	ACE, 900	2, 10
F7	43	Nucleus 24RE	R	Freedom	ACE, 900	4, 3
F10/F11	13	Nucleus 24RE/24RE	R, L	CP810, CP810	ACE, 900 (R & L)	5, 5/11, 10
N5	51	Nucleus CI512	R	CP810	ACE, 720	0, 5
C8	63	Clarion CII HF 1J	L	Harmony	HiRes-P w/Fidelity 120, 3712	7, 10
C14	16	Clarion CII HF 1J	R	Auria	CIS, 829	10, 0
C17	13	HiRes 90K HF 1J	R	Harmony	HiRes-P w/Fidelity 120, 3712	5, 11
C24	76	Clarion CII HF 1 + p	R	Harmony	HiRes-S w/Fidelity 120, 3712	9, 5
C26	70	HiRes 90K HF 1J	R	Harmony	HiRes-S w/Fidelity 120, 2750	2, 11
C27	48	Clarion CII HF 1J	L	Harmony	HiRes-P, 3480	8, 3
C29	34	HiRes 90K HF 1J	R	Harmony	HiRes-S w/Fidelity 120, 3712	3, 8
C35	87	HiRes 90K HF 1J	R	Harmony	HiRes-S w/Fidelity 120, 2184	3, 0

pps = pulses per second (per channel); y, m = years, months; duration of CI use at testing; p = positioner; HF = HiFocus; R = right; L = left.